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STUDY ON RADIO DIRECTION ESTIMATION ALGORITHMS

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Abstract : The presented paper analyses the steps by which radio direction estimation algorithms are used to visualize the direction from which a radio signal originates. This study aims to use ULA (Uniform Linear Array) and URA (Uniform Rectangular Array) antennas and integrate them into a simulation in order to find the direction of origin of the signals, what the contrast between the phase and time differences is when the signal reaches the antennas and how the systems for estimating the directions of arrival (DOA) affect the signal at the receptor . The difference between ULA and URA antennas is exemplified by using them in a more complex system that can be implemented physically and not just digitally. These two arrays of antennas have several particularities such as the DOA algorithms used by each antenna, its angled directions and their representation from a matrix point of view. The simulation was conducted as a preliminary study for a hardware implementation of this system using a USRP N 310 software defined radio platform.
Key words : radio, simulation, direction of arrival, antenna, algorithm.

1. INTRODUCTION

This paper explores several methods for estimating the direction of arrival (DoA) of a received radio signal by determining its precise azimuth and elevation angles. The study focuses on simulation techniques such as Uniform Linear Array (ULA), Uniform Rectangular Array (URA), Minimum Variance Distortion less Response (MVDR), and Multiple Signal Classification (MUSIC). In addition to simulation, the work includes a planned hardware implementation using the USRP N310 software-defined radio. It should be noted, however, that the hardware implementation has not yet been realized at the current stage of the work.

2. MATERIALS AND METHODS

2.1 MATLAB Simulation Software

The program used to analyse the behaviour of a radio wave, determining the direction of origin, as well as azimuth and elevation angles, is MATLAB. For the purpose of estimating the radio direction, two types of antennas will be used: ULA (Uniform Linear Array) and URA (Uniform Rectangular Array). They use specific methods that will allow the differences between them to be compared, the performance of each method being evaluated in terms of the accuracy of the estimation of steering angles [1].

2.2 Azimuth angle

The angle between a reference direction (usually the north) and the horizontal projection of an object is defined as an azimuth angle. It is measured clockwise from 0 degrees to 360 degrees. In this project it is used to observe the horizontal direction from which a signal comes (a group of antennas will be used as a reference point or an array of antennas). In radio direction estimation systems, this angle is used to direct the signal flow to a particular device, identify a signal source, and locate objects through reflected signals. This angle can be analysed with ULA and URA antennas.

2.3 Elevation angle

This angle represents the angle between the direction of an object and the horizontal plane. It can be measured from 0 degrees to 90 degrees. In radio direction systems, the elevation angle is used to indicate the height from which a signal originates in relation to the horizontal plane of an antenna group or antenna array (both types will be exemplified in this project). The elevation angle can be used in DOA (Direction of Arrival) systems to determine the position of an object and to optimize the signal in wireless communications. It can only be viewed in applications using URA (Uniform Rectangular Array) antennas, as this alone allows the simultaneous use of both angles: elevation and azimuth.

2.4 DOA algorithm

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DOA (Direction of Arrival) is a technique used to approximate the direction from which a certain signal originates, i.e. to determine the angle of origin of a signal in relation to an array of antennas (this term is used to describe an array of antennas that function as a set of sensors). This algorithm is based on a set of data collected from several sensors, with the aim of estimating the direction of origin of the signal, by processing the information obtained. DOA algorithms can use several techniques such as beam scan, MVDR and MUSIC, these being specially designed to be able to locate signal sources [2].

2.5 ULA (Uniform Linear Array)

The Uniform Linear Array is an array of antennas that are positioned in a straight line, having equal distances from each other. This configuration is used in radio direction estimation systems. The process of operation of this type of arrangement is very easy to understand. Each antenna in ULA receives signals from different sources causing the signals to arrive with a phase delay conditioned by the angle of arrival of each signal. By comparing these phase shifts, the angle of arrival of the signal can be estimated.

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2.6 URA (Uniform Rectangular Array)

Uniform Rectangular Array is a type of antenna array that is placed in a uniform array configuration, in two dimensions (horizontal and vertical). They are placed as ULA antennas, at the same distance from each other, horizontally and vertically. The main difference between the two types is that the ULA (Uniform Linear Array) covers a one-dimensional line, while the URA (Uniform Rectangular Array) covers a two-dimensional space. The two-dimensional configuration has a wider coverage and offers the possibility of scanning angles from two directions (azimuth and elevation). A signal that reaches an URA will reach the antennas in the array with a different phase shift, depending on the angle of arrival on both the horizontal and vertical axis. In the case of an URA, two angles will be calculated: the azimuth angle and the elevation angle. The phase shifts for each antenna in both directions (horizontal and vertical) are used to estimate these angles.

2.7 Beam scan algorithm

Beam scan is a simple method of estimating the direction of some radio signals in an antenna array system such as ULA and URA. The main idea is to "scan" different angles of arrival of the signal and calculate the signal strength at each angle. This method can be applied in both types of antenna arrays, but there are significant differences in the way the algorithm is implemented for each of them, due to the distinct configurations of the two types of arrays. In estimating angles, for ULA, Beam scan involves scanning the arrival angles of the signal in a single direction (azimuth angle), For URA, it involves scanning two arrival angles, considering both the azimuth angle (in the horizontal plane) and the elevation angle (in the vertical plane). In the case of ULA, the angular resolution of the direction estimate is restricted to a single angle. If two signal sources are almost in the same direction of arrival (but not identical), the Beam scan algorithm may not differentiate them effectively because it only analyses angles on a single (one-dimensional) axis. On the other hand, in the case of the URA array, due to its two-dimensional configuration, the Beam scan algorithm can provide a higher resolution in detecting signals, including those that are close in both the horizontal and vertical planes.

2.8 MVDR algorithm

MVDR (Minimum Variance Distortion less Response) is a beamforming technique (it can focus the signal in a specific direction, making it easier to identify the direction from which the transmitted or received signal has its maximum intensity) that captures the desired signal from a specific direction, while attenuating interference and noise from other directions.

This technique is used for both types of arrays, ULA and URA. The main differences in the use of MVDR are related to the size and complexity of the array. While ULA only allows for single-direction signal estimation, URA extends this capability to three-dimensional space, allowing scanning in both horizontal and vertical directions. This makes MVDR in URA more complex in terms of estimating the covariant matrix, which is essential for estimating the direction from which signals originate, but at the same time more efficient in complex environments where interference comes from multiple angles.

2.9 MUSIC algorithm

MUSIC (Multiple signal classification) is an algorithm that helps to identify the direction of arrival of an emitted radio signal based on spectral analysis and decomposition of the covariant matrix.

This decomposition of the matrix is performed because it is desired to extract useful information from a signal that is then used to find out the direction of arrival of the signal, but also to separate the signals from noise, performing a more accurate spectral efficiency.

This method is used in both ULA and URA systems, which of these types of antenna arrangements is more suitable for performing this technique. In a linear array (ULA), the antennas are placed only on a single axis, if the distance between the antennas is greater than $\lambda/2$, spatial aliasing may occur, which means that different directions of the signal become indistinguishable (signals coming from different angles may appear to be coming from the same direction). For a rectangular array (URA), the antennas are placed in two axes, which allows signals

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to be processed in two different directions (azimuth and elevation), helping to correctly distinguish between signal sources.

3. RESULTS AND DISSCUTIONS

Following several published papers about DOA systems, a simulation of the radio direction estimation system was made using the MATLAB software, materializing several conclusions regarding the use of reception techniques using ULA and URA antennas [4].

3.1 Beamscan, MVDR and MUSIC techniques in an ULA antenna system

In this section, several techniques are explored for estimating the direction of arrival (DOA) of radio signals using a Uniform Linear Array (ULA)**.** Accurate DOA estimation is crucial for applications in radar, wireless communication, and signal processing. Three methods: Beamscan, MVDR (Minimum Variance Distortionless Response), and MUSIC (Multiple Signal Classification) are analysed and compared to assess their effectiveness in detecting and differentiating multiple signals. The study begins with Beamscan**,** a basic method that relies on azimuth angles but struggles to separate closely spaced signals. To improve accuracy, MVDR is introduced, offering better resolution but still facing challenges in distinguishing signals that are too close. Finally, the MUSIC algorithm is tested, demonstrating superior performance by effectively resolving signals even in noisy environments. Through this comparison, we aim to highlight the strengths and limitations of each technique and determine the most reliable approach for precise DOA estimation.

3.1.1 Beamscan-ULA

A simulation was made to estimate the radio direction using two signals in order to observe the difference between the effectiveness of the techniques. The first method, since it is made for a ULA antenna array, only the azimuth angle of the signal can be used.

In MATLAB, a code was created in which the following characteristics were applied: the number of elements in the ULA array, 4 antennas with a spacing of 0.5 meters between them; the angle of the first signal is 40 degrees and the second signal has an angle of -20 degrees (these angles can vary between -90 degrees and +90 degrees); the speed of light together with a frequency of 300 MHz, both in order to be able to perform the wavelength calculation. A 4-antenna ULA was chosen because it can be implemented with the USRP N310, which has only four input channels.

However, as shown in the following figures, using a ULA with 16 antennas leads to significant improvements in the results. In Figure 2, the graph is much more precise, clearly distinguishing between the two signals. In contrast, Figure 1 shows the signals are distinguishable, but with a limited antenna array, the distinction is less clear. Although it's possible to link multiple antennas in the array, a larger antenna configuration is more efficient. The constraint of using the USRP N310 limits the system to only four connected antennas, which affects the antenna array design.

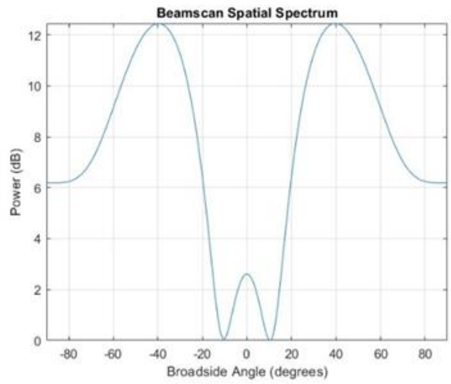

Figure 1 Beamscan Spatial Spectrum with azimuth angles of -40 and 40 degrees using an ULA with 4 elements

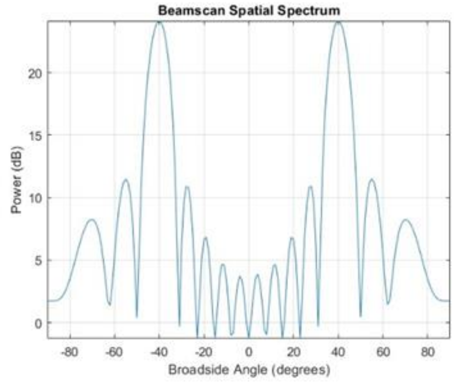

Figure 2 Beamscan Spatial Spectrum with azimuth angles of -40 and 40 degrees using an ULA with 16 elements.

To test the performance of the Beamscan algorithm under conditions where the signals are closer angularly, two experiments were performed. In Figure 3, two signals with angles of -10° and 15° were considered, using a 4-element array.

In Figure 4, the same angles were maintained, but with an array of 16 antennas, to observe how the number of elements influences the resolution and performance of the algorithm in detecting nearby signals.

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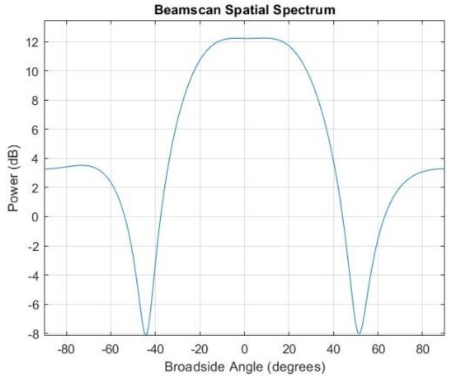

Figure 3 Beamscan Spatial Spectrum with azimuth angles of -10 and 15 degrees using an ULA with 4 elements.

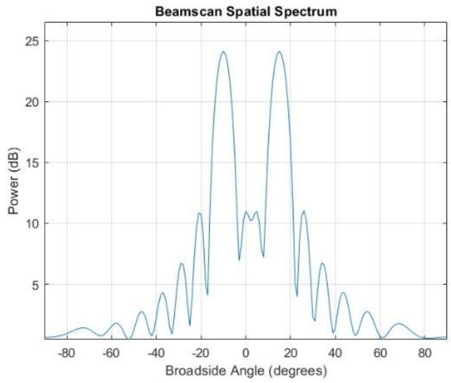

Figure 4 Beamscan Spatial Spectrum with azimuth angles of -10 and 15 degrees using an ULA with 16 elements.

It can be seen that in Figure 3 the two received signals are no longer distinct, which makes the array of 4 antennas not sufficient for the Beamscan algorithm, because it can no longer differentiate the signals located at a small angular distance.

In contrast, in Figure 4, the use of a 16-antenna array allows the Beamscan algorithm to clearly distinguish the two signals, even at an angular difference of only 25 degrees, thus demonstrating its improved ability to resolve close signals when using a larger number of antennas.

Figure 5 illustrates that the Beamscan algorithm detects a single, fainter lobe, instead of the two distinct signals that should be present.

The signals are separated by a 10° angle, and the array configuration includes only 4 elements, which limits the angular resolution capability.

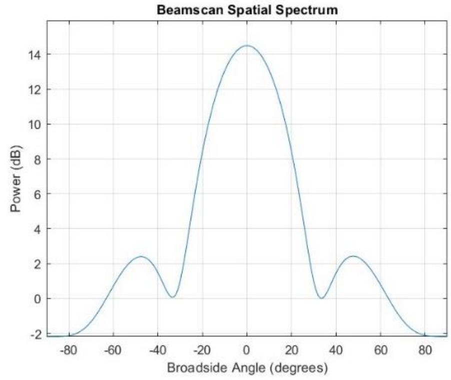

Figure 5 Beamscan Spatial Spectrum with azimuth angles of -5 and 5 degrees using an ULA with 4 elements.

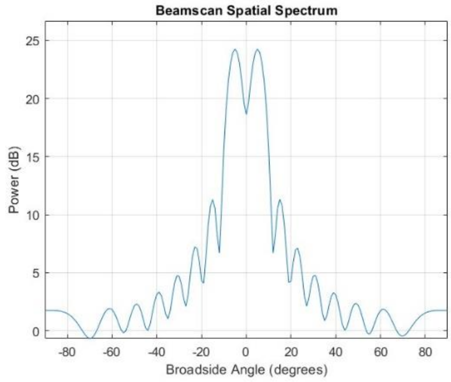

Figure 6 Beamscan Spatial Spectrum with azimuth angles of -5 and 5 degrees using an ULA with 16 elements.

In contrast, Figure 6 clearly highlights the two distinct signals, thanks to the use of an array consisting of 16 antennas. These results show that the performance of the Beamscan algorithm is closely related to the number of elements in the array – a reduced number of antennas does not allow an efficient separation of nearby signals, while a higher number of elements significantly improves the differentiation capacity.

3.1.2 MVDR-ULA

The difference between Figure 7 and Figure 8 lies in the width of the lobes of the detected signals.

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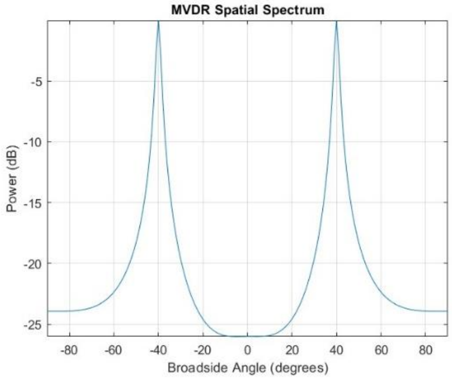

Figure 7 MVDR Spatial Spectrum with azimuth angles of -40 and 40 degrees using an ULA with 4 elements.

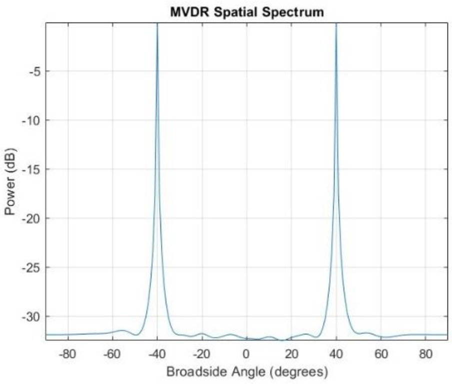

Figure 8 MVDR Spatial Spectrum with azimuth angles of -40 and 40 degrees using an ULA with 16 elements.

In Figure 7, where only 4 antennas were used, the signals appear wider and less angularly precise.

On the other hand, in Figure 8, the use of an array consisting of 16 elements allows to obtain much narrower lobes, which contributes to a more precise location of the direction of origin of the signals.

This comparison highlights that as the number of elements in the array increases, the angular accuracy of the MVDR algorithm improves significantly, allowing for a clearer and more accurate estimate of the signal direction.

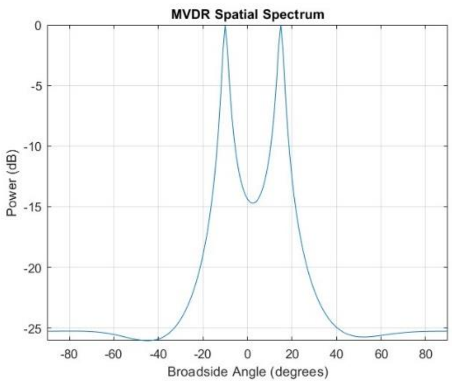

Figure 9 MVDR Spatial Spectrum with azimuth angles of -10 and 15 degrees using an ULA with 4 elements.

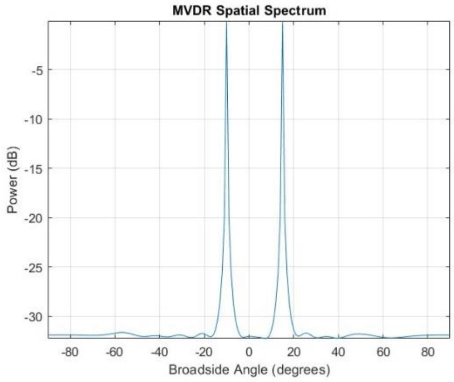

Figure 10 MVDR Spatial Spectrum with azimuth angles of -10 and 15 degrees using an ULA with 16 elements.

Figure 9 presents the tendency of the two signals to partially overlap as a result of the angular proximity between them, which affects the separation capacity when using a small number of elements in the array. In contrast, Figure 10 highlights a clear delimitation of the two signals, thanks to the use of a 16-antenna array.

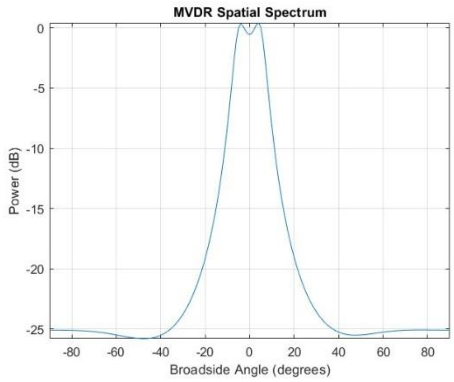

Figure 11 MVDR Spatial Spectrum with azimuth angles of -5 and 5 degrees using an ULA with 4 elements.

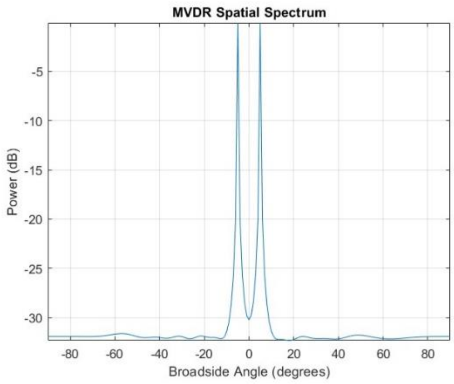

Figure 12. MVDR Spatial Spectrum with azimuth angles of -5 and 5 degrees using an ULA with 16 elements.

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Figure 11 illustrates the results obtained with the MVDR algorithm for the reception of two signals at an angular distance of 10° in the azimuth plane. Even when using an array with a small number of elements, the algorithm manages to highlight, albeit partially, the presence of both signals. In Figure 12, where 16 elements were used in the array, the separation of the two signals becomes much clearer, demonstrating the MVDR algorithm's superior ability to resolve angle-close signals. Compared to Beamscan, MVDR offers better angular resolution, making it more effective in scenarios where signal sources are directionally close.

3.1.2 MVDR-ULA

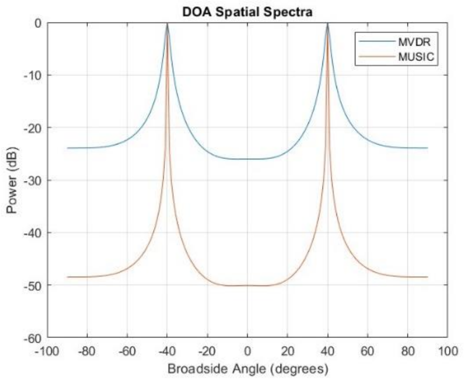

Figure 13 MUSIC Spatial Spectrum with azimuth angles of -40 and 40 degrees using an ULA with 4 elements.

Figure 13 demonstrates a comparison between the MVDR and MUSIC algorithms, in the context of two signals separated by an 80° angle.

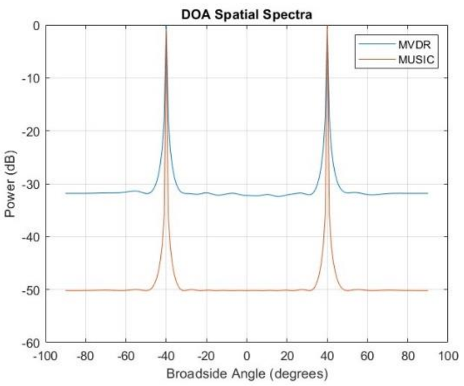

Figure 14. MUSIC Spatial Spectrum with azimuth angles of -40 and 40 degrees using an ULA with 16 elements.

One can observe the behaviour of each algorithm in estimating the direction of arrival (DOA) for a wide angle of separation. Figure 14 illustrates the comparison between the two algorithms again, but this time the superiority of the MUSIC algorithm in terms of signal clarity and uniformity is highlighted. MUSIC provides a more accurate and well-defined representation of signals, compared to MVDR, which underlines its increased efficiency in such scenarios.

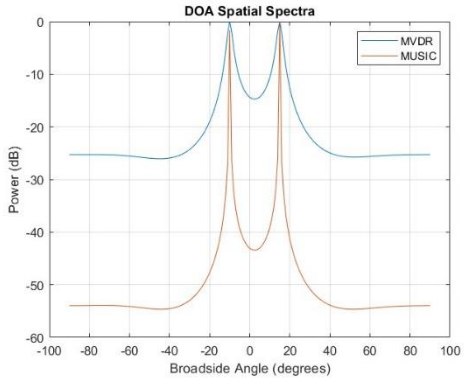

Figure 15. MUSIC Spatial Spectrum with azimuth angles of -10 and 15 degrees using an ULA with 4 elements.

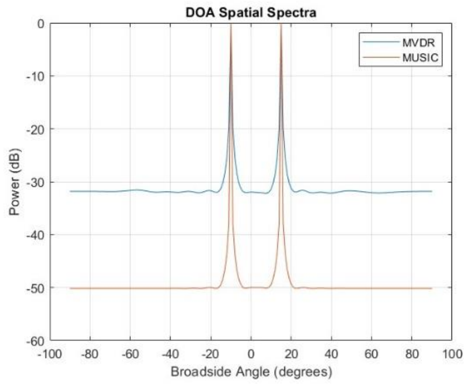

Figure 16. MUSIC Spatial Spectrum with azimuth angles of -10 and 15 degrees using an ULA with 16 elements.

Figure 15 illustrates the same comparison between the MVDR and MUSIC algorithms, but for a small angular distance between the signals, of 25°. Figure 16, where an array of 16 elements was used, shows that the MUSIC algorithm continues to deliver high performance. Comparing the two situations, it can be concluded that MUSIC is able to operate efficiently even with a small number of elements (4 antennas), providing results comparable to those obtained in configurations with a larger number of antennas. However, the increase in the number of elements contributes to improved accuracy and signal separation capacity, highlighting the additional benefits of using a denser array.

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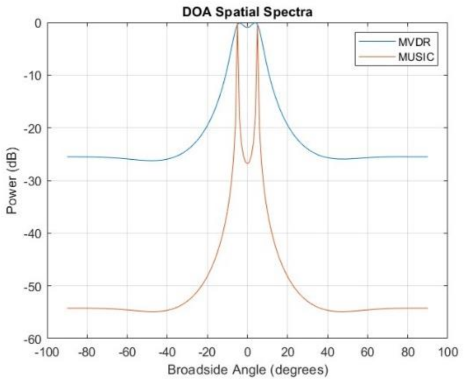

Figure 17 MUSIC Spatial Spectrum with azimuth angles of -5 and 5 degrees using an ULA with 4 elements.

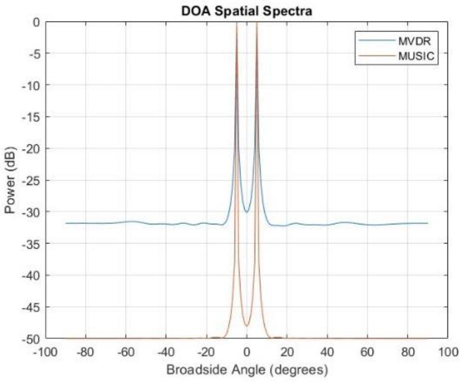

Figure 18 MUSIC Spatial Spectrum with azimuth angles of -5 and 5 degrees using an ULA with 16 elements.

Figure 17 highlights the performance differences between the MVDR and MUSIC algorithms when using a 4-element array. The results show that the MUSIC algorithm provides a higher spectral resolution, managing to more efficiently separate the two received signals, which become clearly visible, unlike MVDR. In Figure 18, the same comparison is made using an array of 16 elements. In this case, both algorithms – both MVDR and MUSIC – offer comparable performance, managing to clearly distinguish the two signals, which demonstrates that, with the increase in the number of antennas, the differences between the two methods diminish.

3.2 Beamscan, MVDR and MUSIC techniques in a URA antenna system

In this section, the performance of different Direction of Arrival (DOA) estimation techniques is analyzed for a Uniform Rectangular Array (URA). Unlike the Uniform Linear Array (ULA), which only considers the azimuth angle, a URA system allows for the estimation of both azimuth and elevation angles, making it more suitable for three-dimensional signal detection. The Beamscan method is first applied to a 2X2 URA and second to a 16x16 URA with specific element spacing, using a 2D Beamscan technique to estimate signal directions. While Beamscan provides a basic visualization of DOA, it has limitations in resolution. Next, the MVDR (Minimum Variance Distortionless Response) method is explored, offering higher accuracy but suffering from excessive sensitivity, which can sometimes lead to errors in signal direction estimation. Finally, the MUSIC (Multiple Signal Classification) algorithm is evaluated, demonstrating superior accuracy in estimating both azimuth and elevation angles, albeit with increased computational complexity. By comparing these three techniques, the aim is to determine the most effective method for accurately estimating DOA in URA systems while considering their respective strengths and weaknesses.

3.2.1Beamscan-URA

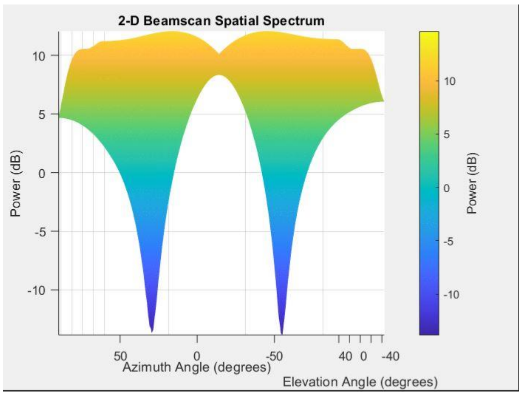

Figure 19. 3D spectrum for a 2-D Beamscan. For the first signal was used the elevation angle of 30 degrees and for azimuth angle -40 degrees. For second signal used the elevation angle -25 degrees and for azimuth angle 40 degrees using an URA with 4 elements.

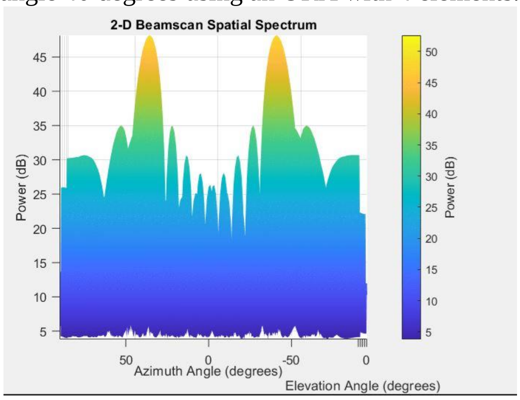

Figure 20 3D spectrum for a 2-D Beamscan. For the first signal was used the elevation angle of 30 degrees and for azimuth angle -40 degrees. For second signal used the elevation angle -25 degrees and for azimuth angle 40 degrees using an URA with 16x16 elements.

Figure 19 illustrates the three-dimensional spectrum generated by the Beamscan algorithm using a uniform

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rectangular array (URA) of type 2×2. This configuration allows the simultaneous representation of the directions of arrival in the azimuth and elevation planes. However, due to the small number of elements, the spatial resolution is limited. Figure 20 shows a significantly improved version of the same algorithm, where a 16×16-element URA array was used. The results show a clear and precise separation of the two signal sources, highlighting the advantage of using a dense array of antennas to achieve higher resolution in both planes.

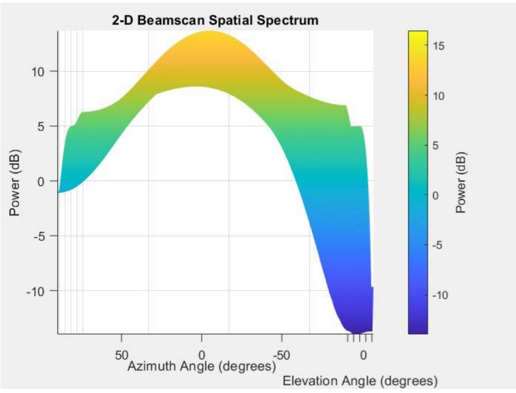

Figure 21 3D spectrum for a 2-D Beamscan. For the first signal was used the elevation angle of 20 degrees and for azimuth angle -10 degrees. For second signal used the elevation angle -10 degrees and for azimuth angle 15

Figure 21 presents the limitations of the Beamscan algorithm when the two signals are angled together, using a 2×2 size URA antenna array. In this configuration, the algorithm is no longer able to properly distinguish the two sources, due to the low spatial resolution. In contrast, Figure 22 highlights a clear separation of the same close signals, thanks to the use of an array of antennas 16×16.

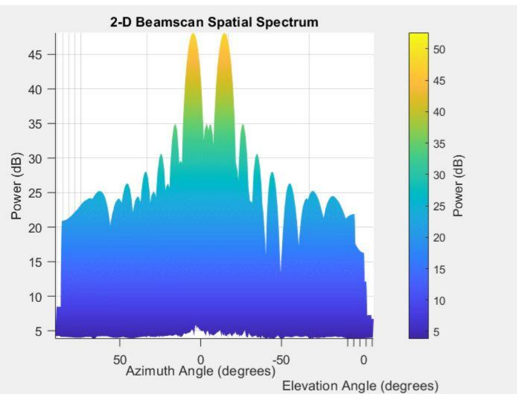

Figure 22 3D spectrum for a 2-D Beamscan. For the first signal was used the elevation angle of 20 degrees and for azimuth angle -10 degrees. For second signal used the elevation angle -10 degrees and for azimuth angle 15 degrees using an URA with 16x16 elements.

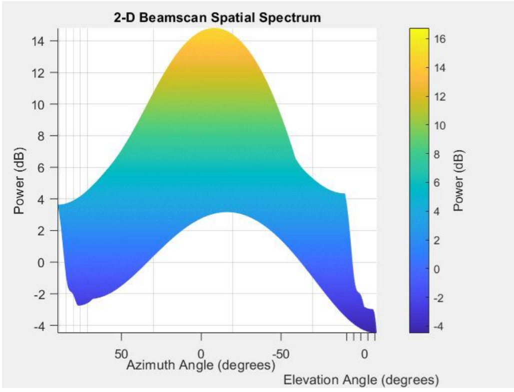

Figure 23 3D spectrum for a 2-D Beamscan. For the first signal was used the elevation angle of 10 degrees and for azimuth angle -5 degrees. For second signal used the elevation angle 5 degrees and for azimuth angle 5 degrees using an URA with 4 elements.

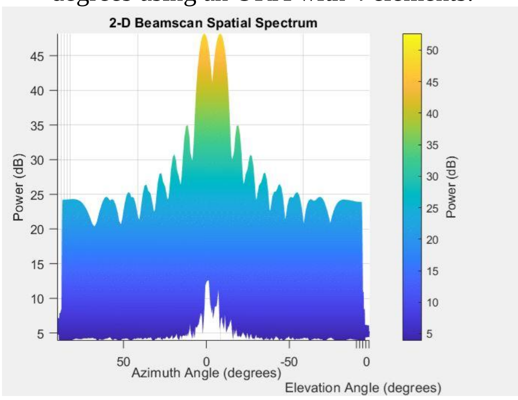

Figure 24. 3D spectrum for a 2-D Beamscan. For the first signal was used the elevation angle of 10 degrees and for azimuth angle -5 degrees. For second signal used the elevation angle 5 degrees and for azimuth angle 5 degrees using an URA with 16x16 elements.

Figure 23 shows the case of the closest signals analysed in the project, where the Beamscan algorithm is no longer able to distinguish them as separate sources, but interprets them as a single signal, due to the limited spatial resolution associated with a small matrix. In contrast, Figure 24 demonstrates that, even under conditions of accentuated angular proximity in azimuth and elevation, the Beamscan algorithm can efficiently separate the signals, provided that an array with a large number of antennas is used.

3.2.2 MVDR-URA

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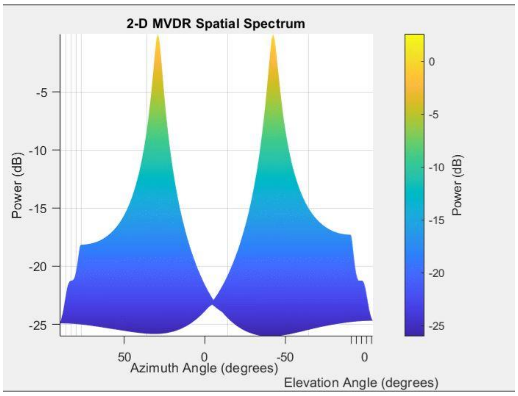

Figure 25 3D spectrum for a 2-D MVDR. For the first signal was used the elevation angle of 30 degrees and for azimuth angle -40 degrees. For second signal used the elevation angle -25 degrees and for azimuth angle 40 degrees using an URA with 4 elements.

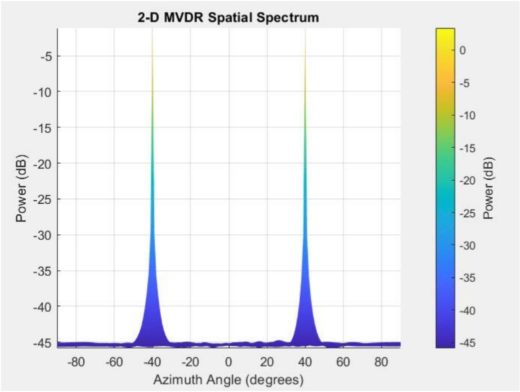

Figure 26 3D spectrum for a 2-D MVDR. For the first signal was used the elevation angle of 30 degrees and for azimuth angle -40 degrees. For second signal used the elevation angle -25 degrees and for azimuth angle 40 degrees using an URA with 16x16 elements.

Figure 25 highlights the ability of the MVDR algorithm to detect two signals located at a greater angular distance, using an array of 4 antennas. Although the separation is visible, the resolution remains limited. In Figure 26, the same situation is analysed with the help of an extended array of 16×16 elements, in which case the signals are much better defined and clearly separated.

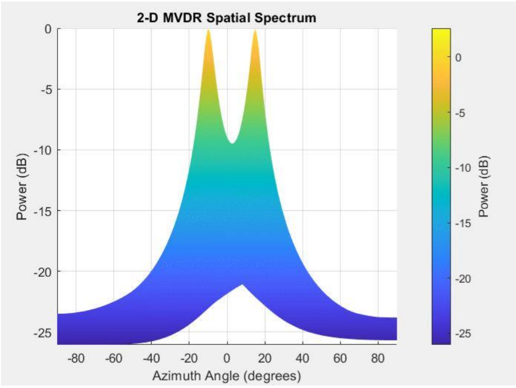

Figure 27 3D spectrum for a 2-D MVDR. For the first signal was used the elevation angle of 20 degrees and for azimuth angle -10 degrees. For second signal used the elevation angle -10 degrees and for azimuth angle 15 degrees using an URA with 4 elements.

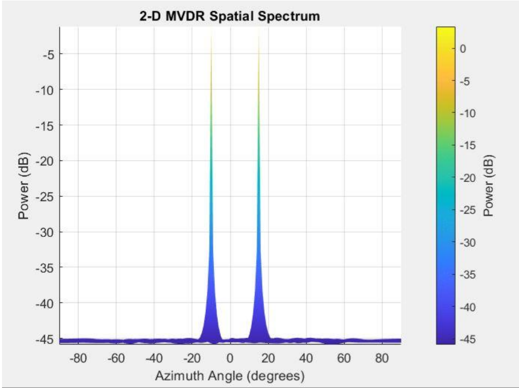

Figure 28 3D spectrum for a 2-D MVDR. For the first signal was used the elevation angle of 20 degrees and for azimuth angle -10 degrees. For second signal used the elevation angle -10 degrees and for azimuth angle 15 degrees using an URA with 16x16 elements.

Figure 27 illustrates two signals that, although close angularly, are still detected as distinct sources by the MVDR algorithm, using a small array. However, the analysis in Figure 28 shows a much clearer separation of signals when using a large array. This confirms that the performance of the MVDR algorithm is significantly improved with the increase in the number of elements in the antenna array, which allows for more accurate estimation and higher spatial resolution.

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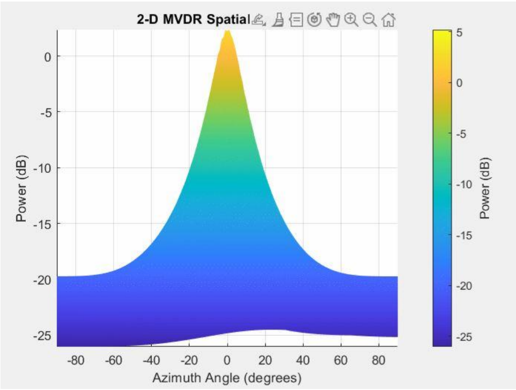

Figure 29 3D spectrum for a 2-D MVDR. For the first signal was used the elevation angle of 10 degrees and for azimuth angle -5 degrees. For second signal used the elevation angle 5 degrees and for azimuth angle 5 degrees using an URA with 4 elements.

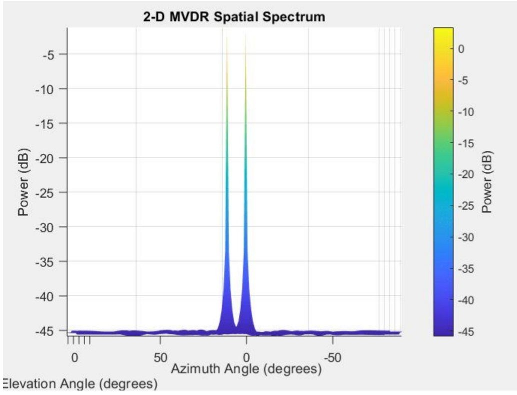

Figure 30 3D spectrum for a 2-D MVDR. For the first signal was used the elevation angle of 10 degrees and for azimuth angle -5 degrees. For second signal used the elevation angle 5 degrees and for azimuth angle 5 degrees using an URA with 16x16 elements.

Figure 29 highlights the limitations of the MVDR algorithm in the case of estimating two signals very close angularly, when using a URA (Uniform Rectangular Array) configuration with only 4 elements. In this situation, the algorithm is no longer able to correctly distinguish the two sources, due to the low spatial resolution. In contrast, Figure 30 demonstrates that by using a larger URA configuration, MVDR is able to efficiently identify and separate even the closest signals.

3.2.3 MUSIC-URA

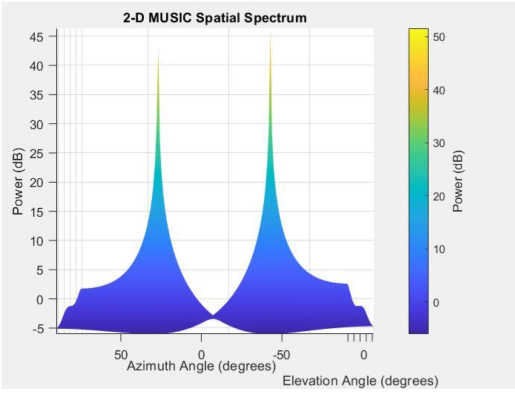

Figure 31 3D spectrum for a 2-D MUSIC. For the first signal was used the elevation angle of 30 degrees and for azimuth angle -40 degrees. For second signal used the elevation angle -25 degrees and for azimuth angle 40 degrees using an URA with 4 elements.

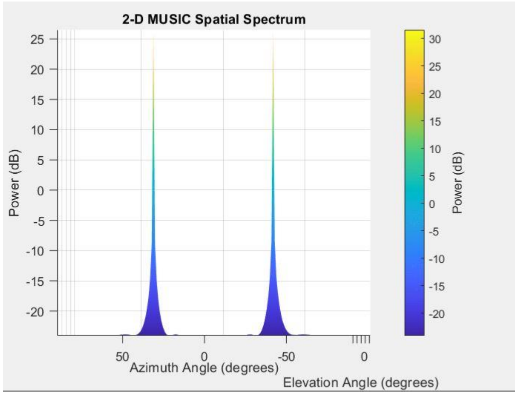

Figure 32 3D spectrum for a 2-D MUSIC. For the first signal was used the elevation angle of 30 degrees and for azimuth angle -40 degrees. For second signal used the elevation angle -25 degrees and for azimuth angle 40 degrees using an URA with 16x16 elements.

Figure 31 demonstrates the performance of the MUSIC algorithm compared to MVDR, using a 4-antenna URA configuration. It is noted that MUSIC provides superior spectral separation and more accurate signal localization, even under conditions with a low number of elements. In Figure 32, where an extended array of 16×16 elements was used, the MUSIC algorithm shows a significantly improved performance, with a much more clearly defined spectrum and a precise distinction between signal sources.

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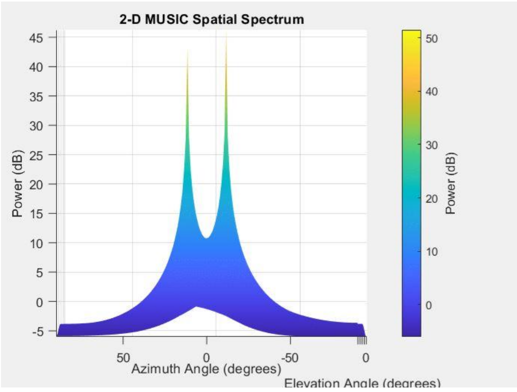

Figure 33 3D spectrum for a 2-D MUSIC. For the first signal was used the elevation angle of 20 degrees and for azimuth angle -10 degrees. For second signal used the elevation angle -10 degrees and for azimuth angle 15 degrees using an URA with 4 elements.

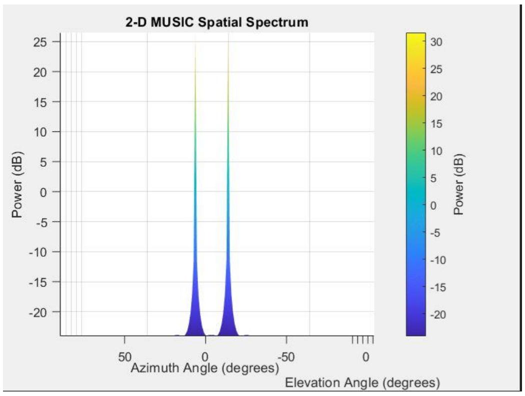

Figure 34 3D spectrum for a 2-D MUSIC. For the first signal was used the elevation angle of 20 degrees and for azimuth angle -10 degrees. For second signal used the elevation angle -10 degrees and for azimuth angle 15 degrees using an URA with 16x16 elements.

Figure 33 illustrates the result of the MUSIC algorithm in the case of two angularly close signals, showing a superior separation capacity compared to the Beamscan and MVDR algorithms in similar configurations. Although the number of elements in the array is small, MUSIC still manages to partially distinguish the two sources. In Figure 34, the use of an extended array leads to significantly improved performance, with a clear and well-defined separation in the spectrum.

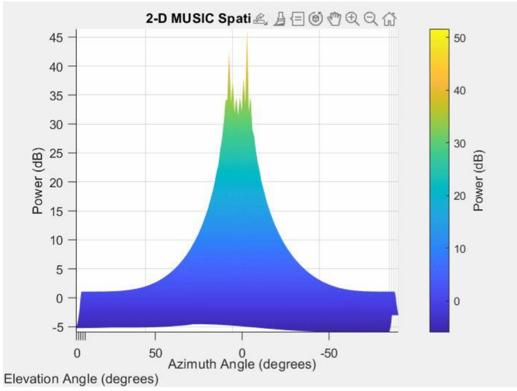

Figure 35 3D spectrum for a 2-D MUSIC. For the first signal was used the elevation angle of 10 degrees and for azimuth angle -5 degrees. For second signal used the elevation angle 5 degrees and for azimuth angle 5 degrees using an URA with 4 elements.

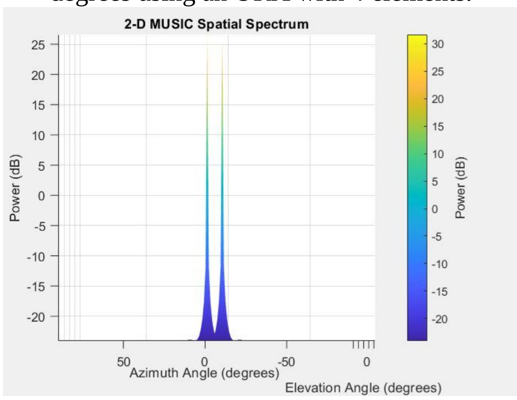

Figure 36 3D spectrum for a 2-D MUSIC. For the first signal was used the elevation angle of 10 degrees and for azimuth angle -5 degrees. For second signal used the elevation angle 5 degrees and for azimuth angle 5 degrees using an URA with 16x16 elements.

Figure 35 highlights the ability of the MUSIC algorithm to detect the presence of two signals very close angularly, even under the conditions of using an URA matrix with only 4 elements. Although the resolution is limited, the algorithm manages to suggest the existence of two distinct sources. In Figure 36, where a considerably larger array size was used, the two signals are clearly separated and well defined in the spectrum, demonstrating the superior efficiency of the MUSIC algorithm when supported by an extended antenna array configuration.

4. CONCLUSIONS

Following the analysis of the methods for estimating the direction of radio signals using the Beamscan, MVDR and MUSIC algorithms on ULA (Uniform Linear Array) and URA (Uniform Rectangular Array) antenna arrays, significant differences were highlighted in terms of precision, complexity and sensitivity of each technique. The results obtained demonstrated that Beamscan is a simple method, but with low resolution, being limited in the separation of nearby signals; MVDR offers higher accuracy, but is sensitive to noise and interference, which can affect the accuracy of the estimates, and MUSIC has proven the highest accuracy in estimating azimuth and elevation angles, managing to identify close signals accurately, but it is the most complex method in terms of calculations. Thus, MUSIC proves to be the best performing method, but its implementation requires greater algorithmic resources and precise mathematical modelling. The choice of the optimal method depends on the application context and the requirements of the system in terms of processing accuracy and efficiency [6].

6. ACKNOWLEDGMENTS

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